Wall Material and Capping Effects on Microlysimeter Temperatures and Evaporation

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ABSTRACT

The microlysimeter (ML) is useful for measurements of evaporation from soil but questions persist regarding correct ML design. We studied the effects of length and wall material on evaporation and the effects of wall material and capping on ML temperatures. Cylindrical steel and plastic MLs of 10, 20 and 30 cm lengths and 8.8 cm outside diameter were used in 2 field experiments on a bare clay loam. Steel MLs significantly underestimated 8 day cumulative evaporation compared to plastic MLs for 20-cm lengths. Steel MLs conducted heat more easily and their surfaces were significantly cooler during the day and warmer at night than either plastic MLs or the adjacent field soil. Capping the bottoms with 0.6 cm thick plastic disks caused accumulation of heat in the MLs. For plastic MLs only the 20 and 30 cm lengths were long enough for continuous use over 9 days under our conditions. It was unclear if cumulative evaporation varied with length for steel MLs. We recommend that walls be constructed of material with low thermal conductivity and that end caps be designed to maximize thermal transfer between the soil inside and below the ML. A length of at least 30 cm is recommended if measurements at the same location over several days are needed.

Evaporation from the soil surface can be estimated using microlysimeters (Russell, 1939; Boast and Robertson, 1982; Salehi, 1984; Boast, 1986), also known as evaporimeters (Walker, 1983). Microlysimeters (MLs) are tubes inserted into the soil, removed with the soil inside intact, and then capped at their bottoms. They are replaced in holes in the soil such that the surface of the soil in the tube, the top of the tube, and the surrounding soil surface are all at the same elevation. They are periodically removed and weighed in order to estimate evaporation. This procedure cannot be applied indefinitely since the ML soil water content will eventually differ from that of the surrounding soil.

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Various problems have been associated with the use of MLs. Salehi (1984) found that the soil surface temperature in steel MLs was lower than that of adjacent soil and suggested that the steel walls conducted heat downward into the soil. Walker (1983) found no such temperature differences using plastic MLs and suggested that metal tubing not be used because of possible heat conduction into or out of the wall. The thermal conductivity of carbon steel is about 3 orders of magnitude larger than that of rigid polyvinyl chloride (PVC) plastic (4.0×10^{-2} and 1.5×10^{-5} J s^{-1} m^{-1} °K^{-1}, respectively; Touloukian et al., 1970). The thermal conductivity of PVC is close to that of very dry mineral soil so that PVC should act as a thermal insulator in a ML. Length has an important effect on ML evaporation estimates, with the shortest lengths causing underestimation of evaporation during drying periods (Boast and Robertson 1982; Shawcroft and Gardner 1983). Klocke et al. (1990) compared evaporation under a corn canopy from MLs made from 20 cm long, 15 cm inside diameter plastic pipe with evaporation from MLs consisting of 6 cm long, 7.6 cm inside diameter metal soil core retaining rings. The plastic MLs were capped with galvanized steel and reweighed daily. The metal MLs were placed in a steel sample can, weighed, replaced in the field (still in the can) and reweighed the next day, after which they were discarded. They found that the steel MLs gave 0.2 mm per day less evaporation than the plastic (significant at 0.025 level) and attributed the difference to soil water extraction by plant roots. They theorized that this extraction caused the soil to be drier in the steel MLs, causing evaporation to be less, even though water content in the plastic MLs was matched to field water content after every irrigation (plastic MLs were removed from the field during irrigation). They did not address the possible differences in evaporation due to ML length or wall material.

Capping of the ML bottom is necessary to prevent soil or water from being lost and to ensure that mass changes are due to evaporation alone. Walker (1983) discussed the problem of lack of drainage from MLs due to the cap. Todd et al. (1991) used plastic MLs with galvanized steel bottoms but did not discuss their reasons

Abbreviations: DOY, day of the year; ML(s), microlysimeter(s); PVC, polyvinylchloride.

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for choosing these materials. Lascano and van Bavel (1986) covered their ML bottoms with Al foil but also did not discuss reasons. They replaced their 13 cm long, 7.4 cm inside diameter aluminum MLs either daily, or every other day when the soil was dry, and found that average cumulative evaporation (three drying cycles) was within 0.2 cm of that calculated from soil water content profiles measured daily to 0.4 m. Some researchers have used caps made from thermally insulating materials such as rubber stoppers (Salehi, 1984, Boast and Robertson, 1982). The effect of insulating caps on the soil heat flux and energy balance in MLs has not been previously measured.

The goals of this study were four fold. First, the thermal regimes of MLs with bottoms capped with plastic disks, uncapped MLs, and adjacent field soil were compared to see if capping had a significant effect on heat flow. Second, the thermal regimes of plastic MLs, steel MLs, and adjacent field soil were compared to see if the wall material had a significant effect on heat flow. Third, cumulative evaporation from steel and plastic MLs was compared. Fourth, cumulative evaporation over several days after an irrigation for MLs of different lengths was compared.

MATERIALS AND METHODS

Two field experiments were conducted in March and April 1985 at the University of Arizona's Marana Agricultural Center (626 m elevation above mean sea level, 32.5 degrees north latitude) about 50 km NW of Tucson. A 1 ha area was used in Field E-2 under the second span of a lateral move sprinkler with low pressure circular spray nozzles. The soil is a Pima clay loam, fine-silty, mixed, thermic family of Typic Torrifluvents. A uniform clay loam surface layer extends to about 90 cm depth and grades into fine sandy loam (Post et al. 1978).

Plastic MLs were 8.15 cm inside diameter with 0.35-cm wall thickness and were made from white PVC pipe. They were tapered on the bottom using a lathe to ease installation. Steel MLs were 8.5 cm inside diameter with 0.15 cm wall thickness and were made of electrical conduit (electromechanical tubing).

Due to the plasticity and stickiness of the soil, pushing the MLs into the soil immediately after an irrigation was not possible. Therefore, installation was on day of year (DOY) 88, 1985, 4 days after a preliminary irrigation of 4.2 cm, when the soil was more cohesive. Installation was done with a tool consisting of a machined metal head that covered the top of the ML and that was fitted with a slide hammer. The tool allowed the direction of installation to be kept vertical and ensured that each hammer blow would be centered on the axis of the ML. This technique minimized wobbling of the ML during installation and thus minimized soil fracturing and void formation along the ML walls. The maximum compaction observed during installation occurred with the 30 cm MLs and was less than 1 cm. On DOY 91 an irrigation of 2.1 cm was applied with the lateral move sprinkler. The soil surface was immediately puddled and sealed by the large drops from the sprinkler. Based on our experience, no preferential channeling of water along the ML walls was expected. Microlysimeters were extracted and capped and thermistors were installed on DOY 92, the day after irrigation. Extraction was accomplished by twisting the ML around its axis to break the soil column at the bottom, followed by pulling the ML vertically leaving a round hole. Two 0.6 cm diameter holes, drilled on opposite sides of the ML about 1 cm from the top, facilitated removal by providing attachment points. All caps were 8.8 cm diameter PVC disks (0.6 cm thick) held in place by package sealing tape. Each ML was returned to its own hole which was lined with a plastic bag to prevent soil from adhering to the outside of the ML.

The thermal regimes of plastic and steel MLs, and the effects on temperature of capping vs. not capping the ML bottoms, were both studied in the experiment marked Thermal Regime in Fig. 1. Soil contact at the bottom of the uncapped MLs in this experiment was left undisturbed so that heat flux would not be inhibited. Holes for insertion of thermistors had previously been drilled in the sides of the MLs at 1 cm, 15 cm and 30 cm depths. Thermistors were pushed in from the side and centered at the vertical axes of the MLs. The thermistors at 15 and 30 cm depths were inserted horizontally into the soil. The surface thermistor was pushed upward at an angle through the hole at 1 cm depth until the tip of the thermistor had just begun to disturb the surface. The disturbed soil was moist and was carefully repacked over the thermistor using a single finger. The thermistor tip could be felt and was estimated to be no more than 0.1 cm below the soil surface. The Campbell Scientific Inc. Model[1] 107 thermistors were modified to be water resistant by dipping in hot melt glue and inserting into heat shrink tubing which was then shrunk, forcing out the extra glue, and crimped at the tip until cool. Thermistors were calibrated prior to the experiment. Thermistors were scanned every

15 minutes by 2 Campbell Scientific model 21X dataloggers which recorded the average of 6 readings taken at 10 s intervals. Field soil temperatures were measured at two sites using similar techniques to install thermistors about 10 cm horizontally from the sides of 30 cm deep holes that were then backfilled (Fig. 1). For each depth and each ML, daily temperature means, maxima and minima were calculated for the 24 h period from midnight to midnight.

Length and wall material effects on ML evaporation were measured in the experimental design marked Evaporation in Fig. 1. Plastic MLs were 10.5, 20.5 and 30.5 cm long. Steel MLs were 11.1, 21.1 and 31.1 cm long. Third and fourth replicates of both plastic and steel 30-cm MLs were installed with thermistors in the Thermal Regime experiment (capped MLs) and so were weighed only on the first and last days of the experiment. Weighing of the MLs started on the day after irrigation (DOY 92) and continued for 9 days.

Moving from east to west in the Evaporation experiment, MLs were extracted, cleaned, capped on the bottom, weighed and reinstalled between 8:30 and 15:15 MST on DOY 92. Evaporation was measured by weighing to 1 g with a large triple beam balance installed in a wooden box as protection against wind. The lengthiness of the extraction and cleaning process precluded measurement of a full day's evaporation on the first day after irrigation (DOY 92). Weighing of MLs on subsequent days was accomplished within a half-hour immediately after sunrise. For the remainder of this paper we will refer to evaporation for a particular day, e.g. evaporation for DOY 93. This would be the evaporation that occurred during the 24 hours from the time of weighing on DOY 93 to the time of weighing on DOY 94.

Daily changes in mass were converted to equivalent depths of evaporation. On DOY 101 the MLs were removed, weighed and soil was extracted, dried and weighed again. Bulk density was calculated from dry soil mass and ML volume, and final gravimetric and volumetric water contents were calculated. Also on DOY 101, the adjacent field soil was sampled to depths of either 10, 20 or 30 cm with a King tube on opposite sides of each ML of corresponding length, within 15 cm of the ML. Gravimetric water contents were calculated and converted to volumetric water content using the bulk density values obtained from the ML data. Data were analyzed with t tests and pooled t tests (Montgomery, 1976, p. 24) for hypotheses concerning two means, and were analyzed with Duncan multiple range tests (SAS Inst., 1987) for hypotheses concerning three means.

RESULTS

Thermal Regime

We began data analysis on DOY 93 because installation of thermistors on DOY 92 caused soil disturbance and because only a partial day's data were obtained on DOY 92. Soil temperatures at all depths showed a strong linear warming trend of 6 to 7 °C during the experiment for all ML treatments and for the field soil (Fig. 2 and 3) indicating substantial net downward heat flux. Both steel and plastic MLs gave temperature maxima at the surface that were lower than maxima measured in the adjacent field soil, with maxima for steel MLs being slightly lower than those for plastic (Fig. 3). Examination of the diurnal soil temperature regime at 3 depths (surface, 15 cm and 30 cm) showed marked differences between steel and plastic MLs (Fig. 4 and 5) with steel MLs giving higher daytime subsurface temperatures and lower daytime surface temperatures. This pattern persisted from DOY 93 to the end of the experiment after DOY 100. Microlysimeters which were closed at their bottoms with plastic disks were generally warmer at 15 and 30 cm depths than those that were left in direct contact with the underlying soil (Fig. 4). Since our concern was with the differences between treatments and not with the time response (i.e., increase in overall temperature over several days) we compared differences in daily temperature maxima, minima and means and in time of occurrence of these. Since the MLs were installed 4 days prior to the irrigation the differences were already well established by DOY 93 and there was no significant time response of the differences for the remainder of the experiment (Huynh-Feldt test, SAS Inst., 1987, p. 605). The lack of time response meant that a repeated measures statistical analysis (SAS Inst., 1987, p. 603) was not necessary. Thus differences were averaged over all eight 24-hour periods (DOY 93 through DOY 100) for analysis.

Temperature maxima and minima of steel MLs occurred more than 1 h earlier at 15 cm depth and more than 2.5 h earlier at 30 cm depth than did maxima and minima in plastic MLs (significant at 0.001 level, Table 1). At the surface there was no such difference. Therefore, the higher thermal conductivity of steel

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service or University of Arizona.

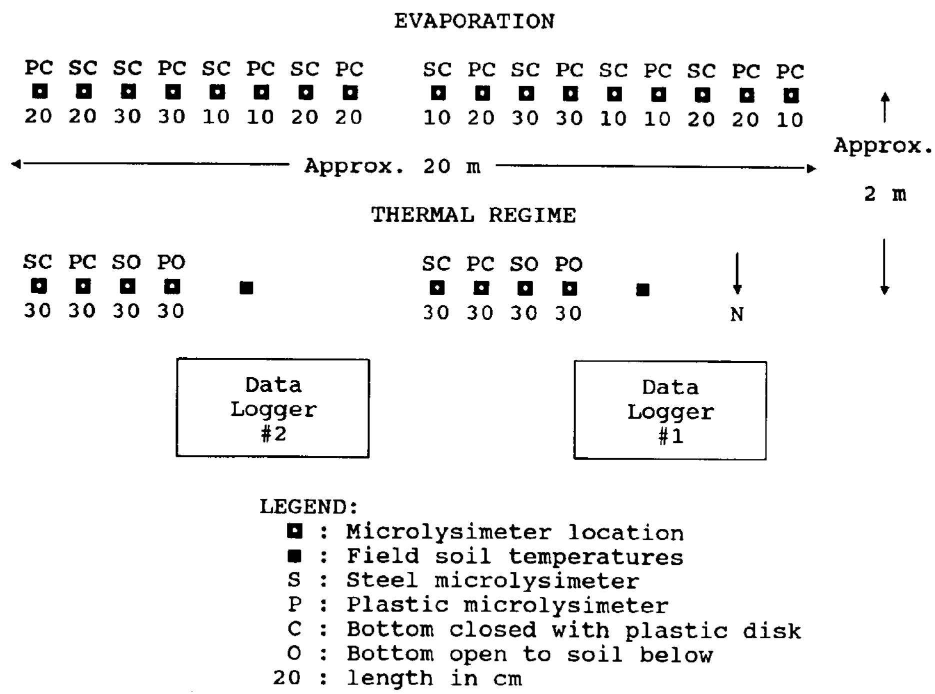

Fig. 1. Field layout schematic. Top row of microlysimeters was weighed daily. Bottom row was instrumented with thermistors. Capped microlysimeters in bottom row were weighed on Day of the Year 91 and at the experiment's end.

compared with plastic is reflected in the apparent thermal conductivities of steel MLs being higher than those of plastic MLs. At the surface, diurnal temperature maxima were 1.5 C higher for plastic than for steel MLs while the minima were 1.2 C lower (significant at 0.001 level, Table 1). At 15 and 30 cm depths this pattern was reversed with the amplitude of the temperature wave being 15% larger for steel than for plastic MLs at 15 cm and 39% larger at 30 cm (0.001 significance level, Table 1). Although the absolute differences in amplitude were 1 C or less this is largely due to damping of amplitude with depth. Again this points to larger heat fluxes due to higher apparent thermal conductivities in steel MLs compared with plastic MLs.

The effects of capping the ML bottoms were somewhat different depending on whether steel or plastic MLs were considered. For both wall materials both the temperature maxima and the mean temperatures were significantly higher at 30 cm (just above the cap) for capped than for uncapped MLs, while temperature minima were not significantly different (Table 2). Duncan multiple range tests (Table 3) were used to compare daily maximum temperatures of capped MLs, uncapped MLs

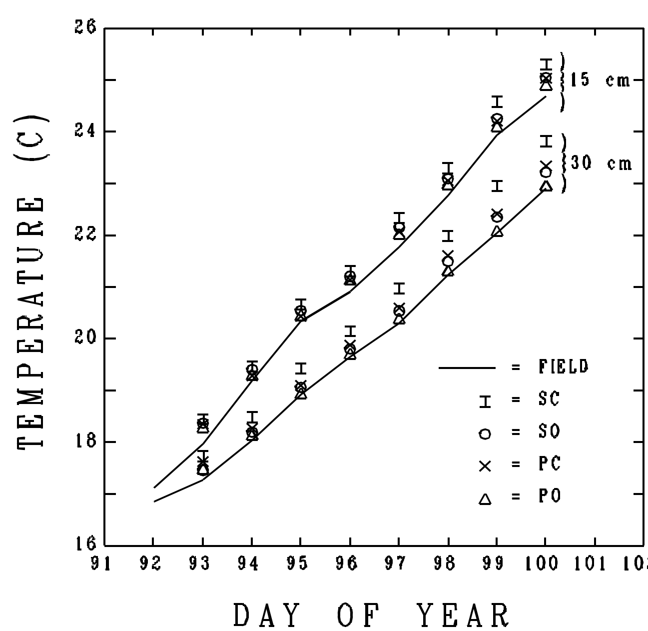

Fig. 2. Daily average soil temperatures at 15- and 30-cm depths for microlysimeters and adjacent field soil (S = steel, P = plastic, O = open bottom, C = capped bottom).

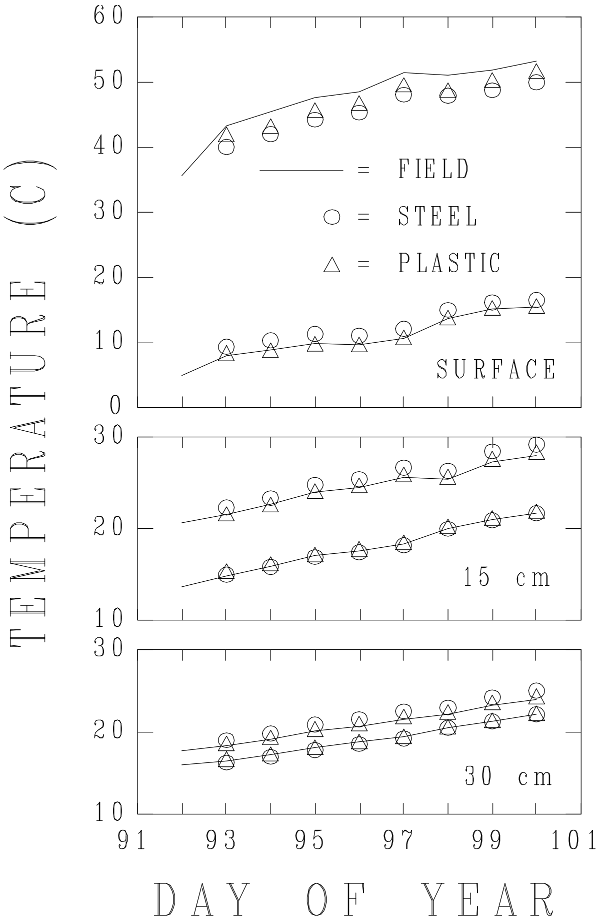

Fig. 3. Mean minimum temperatures and mean maximm temperatures of steel and plastic microlysimeters (averages of capped and open bottomed), and of adjacent field soil at the surface (top), and at 15- (middle) and 30-cm (bottom) depths.

and the field soil because three rather than two treatments were compared. Daily minimum temperatures and daily mean temperatures were also compared among the three treatments (Table 3). These tests showed that temperature maxima of capped plastic MLs were significantly higher (0.52 °C) than those of field soil at 30 cm. This represents about 25% of the temperature amplitude at this depth. The temperature maxima for uncapped plastic MLs were not significantly different from those of field soil at 30 cm. Mean temperatures of both capped and uncapped plastic MLs were significantly warmer than mean temperatures of field soil but capped MLs were 0.31 °C warmer while uncapped MLs were only 0.09 °C warmer than field soil.

Temperature maxima and means for both capped and uncapped steel MLs were significantly higher than those of field soil at 30 cm (Table 3). The warmer subsoil in steel MLs may have resulted in increased nighttime

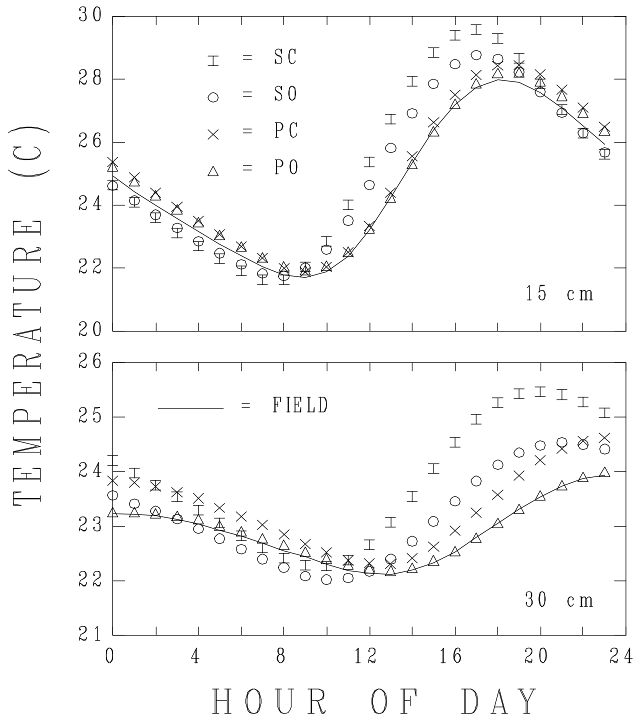

Fig. 4. Average subsurface temperatures for microlysimeter treatments and adjacent field soil, Day of the Year 100 (P = plastic, S = steel, O = open bottom, C = capped bottom).

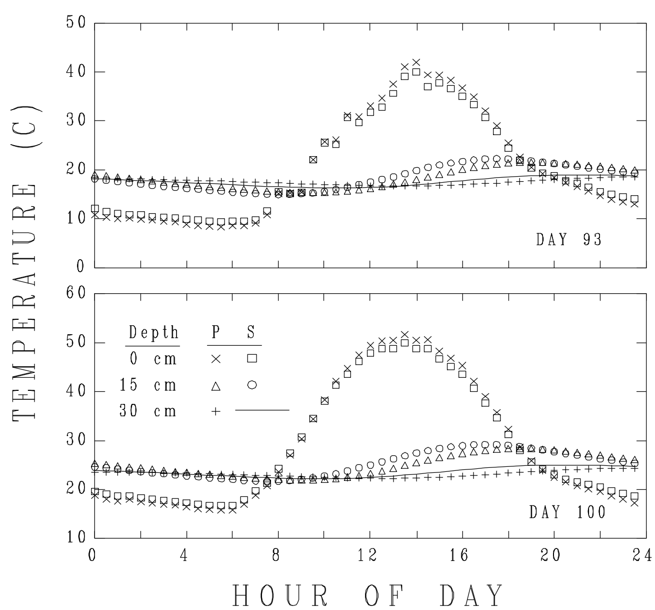

Fig. 5. Soil temperature regime in microlysimeters averaged by wall treatment, Day of the Year 93 and 100 (P = plastic, S = steel).

vapor transport towards the surface. Field evidence for possible vapor transport in steel MLs was observed in the early mornings for several days after irrigation when the soil surfaces were noticeably wetter (darker) in the steel

MLs than in either the adjacent field or in the plastic MLs. Since this wetting caused lower soil albedo in the steel MLs the increased downward soil heat flux may have been partially balanced for short periods of time in the mornings by an increase in absorbed short wave radiation.

Table 1. Comparison, between plastic and steel MLs, of the means† of differences‡ in temperature maxima (δTmax), differences in temperature minima (δTmin), differences in time of maxima (δtMaxT), differences in time of minima (δtMinT), and differences in mean temperature (δMean) .

	Mean	*t* value	Significance
Surface			
δTmax, °C	1.45	3.77	***
δTmin, °C	-1.20	-8.55	***
δtMaxT, h	0.01	0.16	NS
δtMinT, h	-0.02	-0.31	NS
δMean, °C	-0.07	-0.85	NS
15 cm			
δTmax, °C	-0.71	-10.5	***
δTmin, °C	0.30	16.43	***
δtMaxT, h	1.42	31.74	***
δtMinT, h	1.35	27.45	***
δMean, °C	-0.17	-6.77	***
30 cm			
δTmax, °C	-0.56	-10.5	***
δTmin, °C	0.25	6.37	***
δtMaxT, h	2.87	24.41	***
δtMinT, h	2.55	39.81	***
δMean, °C	-0.26	-5.15	***

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively. NS = not significant.
† Means are for 32 samples over 8 days.
‡ Differences were calculated by subtracting the relevant value for steel microlysimeters from that for plastic ones.

At 15 cm the capped MLs of both wall materials exhibited significantly higher temperature maxima and lower temperature minima than did the corresponding uncapped MLs, i.e. a larger amplitude for the diurnal temperature wave (Table 2). Duncan multiple range tests (Table 3) showed that temperature maxima and means of capped plastic MLs were significantly higher than those of field soil at 15 cm, while temperature maxima and means of uncapped plastic MLs were not significantly different from field soil at this depth. Temperature maxima and means of both capped and uncapped steel ML temperatures were significantly higher than those of field soil at 15 cm.

At the surface, plastic MLs were significantly cooler when capped than when uncapped (Table 2). As expected (and shown later), drainage from uncapped MLs was greater than for capped. Lower surface temperatures for capped MLs would be expected on the basis of the capped MLs being wetter and presumably having higher evaporation rates and higher thermal conductivities. Duncan multiple range tests (Table 3) showed that neither temperature maxima nor means for uncapped plastic MLs were significantly different from those of field soil at the surface. Surface temperature maxima and means for plastic MLs with caps were significantly lower than those for adjacent field soil (3.0 and 0.6 °C, respectively).

Table 2. Comparison, between capped and uncapped MLs, of the means† of differences‡ in temperature maxima (δTmax), differences in temperature minima (δTmin) [°C], differences in time of maxima (δtMaxT), differences in time of minima (δtMinT) [hours] and differences in mean temperature (δMean) [°C].

	Plastic			Steel		
	Mean	*t* value		Mean	*t* value	
Surface						
δTmax, °C	-2.31	-7.15	***	0.09	0.36	NS
δTmin, °C	-0.30	-2.26	*	-0.05	-0.78	NS
δtMaxT, h	-0.09	-1.35	NS	-0.11	-2.03	*
δtMinT, h	0.02	1.03	NS	-0.05	-0.66	NS
δMean, °C	-0.79	-23.4	***	0.07	1.04	NS
15 cm						
δTmax, °C	0.22	11.07	***	0.74	5.37	***
δTmin, °C	-0.15	-6.06	***	-0.30	-9.91	***
δtMaxT, h	-0.08	-1.63	NS	-0.30	-4.69	***
δtMinT, h	0.00	0.00	NS	-0.27	-5.14	***
δMean, °C	0.04	2.76	**	0.16	2.55	*
30 cm						
δTmax, °C	0.47	21.37	***	0.79	8.28	***
δTmin, °C	-0.04	-1.27	NS	0.05	0.67	NS
δtMaxT, h	-0.23	-4.17	***	-1.38	-14.3	***
δtMinT, h	-0.47	-4.09	***	-0.55	-6.34	***
δMean, °C	0.22	9.14	***	0.43	5.38	***

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively. NS = not significant.
† Means are for 32 samples over 8 d.
‡ Differences were calculated by subtracting the relevant value for uncapped microlysimeterss from that for capped ones.

The lack of significantly different temperatures between capped and uncapped steel MLs at the surface (Table 2) was probably due to conduction of heat by the steel walls masking the effect of capping. Surface temperature maxima of both capped and uncapped steel MLs were significantly lower than those of field soil while the corresponding temperature minima were significantly higher than those of field soil (Table 3). Not surprisingly then, the mean surface temperature for both capped and uncapped steel MLs was not significantly different from that of field soil.

Capping had minimal effect on the time of temperature maxima and minima at the surface but at 30 cm the capped MLs reached maximum temperatures significantly earlier than uncapped MLs (Table 2) probably due to the insulating effect of the caps.

Mean temperatures of uncapped MLs were closer to those of field soil at equivalent depths than were mean temperatures of capped MLs, except for surface temperatures of steel MLs (Table 3). However, surface temperatures of both uncapped and capped steel MLs were significantly lower than field soil during the day and higher at night (Table 3).

Table 3. Duncan multiple range tests of temperature differences (°C) between field soil, uncapped microlysimeters and capped microlysimeters. For each of three depths (surface, 15- and 30-cm), separate comparisons are shown for daily maximum temperatures, minimum temperatures and mean temperatures; and, for plastic and steel microlysimeters.

Treatment	Means of Temperature		
	Maxima	Minima	Mean Temperature
	°C		
	Plastic		
Surface			
Field	**0.000† A‡**	**0.000 A**	**0.000 A**
Uncapped	**-0.642 A**	**0.265 A**	**0.175 A**
Capped	**-2.958 B**	**-0.038 A**	**-0.612 B**
15 cm			
Field	**0.000 A**	**0.000 A**	**0.000 A**
Uncapped	**0.120 AB**	**0.312 B**	**0.208 A**
Capped	**0.335 B**	**0.166 C**	**0.248 B**
30 cm			
Field	**0.000 A**	**0.000 A**	**0.000 A**
Uncapped	**0.047 A**	**0.121 B**	**0.085 B**
Capped	**0.518 B**	**0.081 B**	**0.307 C**
	Steel		
Surface			
Field	**0.000 A**	**0.000 A**	**0.000 A**
Uncapped	**-3.299 B**	**1.340 B**	**-0.179 A**
Capped	**-3.207 B**	**1.288 B**	**-0.112 A**
15 cm			
Field	**0.000 A**	**0.000 A**	**0.000 A**
Uncapped	**0.570 B**	**0.089 B**	**0.311 B**
Capped	**1.306 C**	**-0.213 C**	**0.476 C**
30 cm			
Field	**0.000 A**	**0.000 AB**	**0.000 A**
Uncapped	**0.444 B**	**-0.174 C**	**0.215 B**
Capped	**1.236 C**	**-0.129 BC**	**0.648 C**

† For ease of comparison to the field soil the means are reported as differences from the field soil measurements, calculated as treatment mean minus field soil mean.
‡ Means that are significantly different at the 0.05 probability level are designated by different letters.

Regardless of wall material, capped MLs were warmer on average at 15 and 30 cm depths than either adjacent field soil or uncapped MLs. Plastic, capped MLs were also cooler at the surface than either uncapped MLs or field soil. This means that during the general warming trend from DOY 93 through DOY 100 the gradient for heat transfer, from the surface to the subsurface soil within the MLs, was lower in the capped than in the uncapped MLs. The same is true for steel MLs. In this context one can ask why the subsurface temperatures in capped MLs were higher than those in either uncapped MLs or field soil. The answer can only be that heat moving downward was trapped by the thermally insulating plastic caps. Given that the incident energy available at the surface was everywhere the same, this translates into a net increase in the heat in the capped MLs. This heat may be available to drive evaporation at the soil surface resulting in higher estimates of evaporation from the ML than would occur if a non-insulating cap were used. The effect of a thermally conducting wall material (e.g. steel or any metal) is to conduct heat downward during the day and upward at night causing significantly lower daytime and higher nighttime surface temperatures. Since less energy would be available to drive evaporation during the day the evaporation estimates from metal MLs would be expected to be lower than actual field evaporation.

Drainage and Evaporation

Final water contents ($m^3\ m^{-3}$) of capped MLs were compared with water contents of adjacent field soil obtained by sampling with a King tube to depths of 10, 20 and 30 cm on DOY 101. All length and wall material treatments were wetter than the adjacent field soil, significantly wetter except for 10 cm long plastic MLs (Pooled t tests on mean water contents, Table 4) indicating that the caps on the ML bottoms stopped drainage from the MLs as expected. For 30 cm plastic MLs the mean difference was 0.016 $m^3\ m^{-3}$ which was equivalent to about 4.8 mm depth of water. A water depth of 4.8 mm represents 55% of mean cumulative (DOY 93 through DOY 100) evaporation for the 30 cm plastic MLs.

The beam balance used to weigh MLs caused considerable noise in the data as evidenced by the occasional negative daily weight changes shown in Table 5. Additional experimental error was introduced on the first day after irrigation by the fact that 6 hours passed between the time that the first ML was weighed at 9:15 MST and the last at 15:15 MST. The lateness of weighing corresponded to a consistent decrease in the evaporation measured for DOY 92. The first 3 MLs weighed gave an average evaporation for DOY 92 of 5.7 mm while the last 3 MLs weighed gave an average evaporation of only 1.5 mm. The 4.2 mm difference is about half of the total evaporation measured on subsequent days. Potential evapotranspiration ranged from 6.6 mm on DOY 92 to 9.4 mm on DOY 98 and averaged 7.6 mm per day during the measurement period (calculated on a half-hourly basis using the method of

Doorenbos and Pruitt (1984) and Pruitt and Doorenbos (1977), DOY 94 excluded due to missing wind data). Although evaporation probably occurred at or near potential rates on DOY 92, data from later days was all well below potential rates (Table 5).

Table 4. Final water contents in capped microlysimeters of 10-, 20-, and 30-cm lengths compared with water contents of adjacent field soil sampled with a King tube.

	10 cm	20 cm	30 cm
		$m^3\ m^{-3}$	
		Steel microlysimeters (S)	
Average	0.164	0.202	0.217
Variance	1.09×10^{-4}	6.21×10^{-5}	2.31×10^{-4}
n	3	3	4
		Plastic microlysimeters (P)	
Average	0.148	0.206	0.221
Variance	3.72×10^{-6}	9.11×10^{-6}	3.32×10^{-4}
n	2	4	4
		King tube (K)	
Average	0.143	0.186	0.205
Variance	2.88×10^{-5}	4.48×10^{-5}	8.95×10^{-5}
n	10	11	16
Pooled *t*-tests	*t'*	df	*t*(0.10)
S vs. K, 10 cm	4.77	11	1.80**
P vs. K, 10 cm	1.36	10	1.81 NS
S vs. K, 20 cm	3.47	12	1.78**
P vs. K, 20 cm	5.47	13	1.77***
S vs. K, 30 cm	1.91	18	1.73*
P vs. K, 30 cm	2.39	18	1.73*

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively. NS = not significant.

Cumulative evaporation (Table 5) was calculated using the time of weighing on DOY 93 as the zero point to avoid the skewed data recorded on DOY 92. In this table the evaporation for a given day is the evaporation occurring between the time of weighing on that day and the time of weighing on the next day. At the 20 and 30 cm lengths, plastic MLs showed more evaporation than did steel (significant at 10% level for 20 cm, t test). Since DOY 92 data were omitted from these comparisons the third replicate of 30 cm MLs (installed with thermistors) could not be included in cumulative evaporation calculations and a t test, of the difference between steel and plastic MLs of 30 cm length, was not practical. There was no significant difference between evaporation from steel and plastic MLs of 10 cm length.

For plastic MLs there was an increase in cumulative evaporation with length, but this was not clear for steel. If heat conduction by steel ML walls lowered the energy available for evaporation then the effect of length would be expected to be lessened. For plastic MLs, the 20 and 30 cm lengths appear to be adequate over the entire 9 day period without a decrease in evaporation due to lack of water flow from below. A similar interpretation for steel MLs was ambiguous due to noise and a non-monotonic response to length possibly due to heat conduction.

SUMMARY

The data and analyses lead to the conclusion that wall material and capping affect the performance of MLs in the field. Steel MLs warmed more rapidly at depth than did plastic, i.e. heat flux density was higher in steel MLs. Surface temperature extremes were less for steel MLs which were cooler than plastic MLs or field soil in daytime, confirming the findings of Salehi (1984). The increased conduction of heat from the soil surface downward in steel MLs resulted in higher subsurface soil temperatures and less evaporation at the surface compared to plastic MLs. The differences in evaporation measured were important for 20 cm long MLs (significant at the 10% level). Our data for plastic MLs suggests that length should not be shorter than 30 cm if the ML is to be left in the field for as long as 9 days under our conditions. The question of length may be avoided by replacing MLs daily as many have done but this makes certain studies impossible. For instance our study was done within the scope of a larger research effort investigating the change in spatial variability of evaporation over time. In order to compare spatial variability from one day to another it was important to sample the same location every day.

It is possible that MLs in general overestimated evaporation in the first few days after irrigation since capping the ML bottoms stopped drainage which left the soil inside wetter than adjacent field soil. Capping also caused a buildup of heat in the bottoms of MLs since the caps were thermal insulators compared to the soil. This may have resulted in overestimation of evaporation by MLs on later days. If the soil were cooling rather than warming, the effect of capping could be to cause a cooler soil in the ML resulting in underestimation of evaporation.

Clearly, ML walls should be made of nonconductive material such as plastic. Even though we did not compare plastic and metal caps, the soil column in our uncapped MLs was undisturbed so that heat flux was not inhibited at the ML bottom. It is clear that MLs should be designed to prevent trapping of heat at the bottom. This might be accomplished by using a thin metal cap if good contact between the cap and the soil above and below can be assured. Another possibility is to use a very thin flexible material that might achieve better

Table 5. Daily and cumulative microlysimeter water content change from Day of the Year 93 to 100.

Wall Type†	Length	Water content change 93	94	95	96	97	98	99	100	Cumulative
	cm	mm equivalent depth of water								
S	10	1.7	1.6	1.2	0.7	1.0	0.7	0.9	0.3	8.2
S	10	1.0	1.7	1.2	1.2	0.5	1.0	1.2	0.2	8.2
S	10	1.6	1.2	0.7	0.7	1.7	0.5	0.7	0.7	7.8
Mean		1.5	1.5	1.0	0.9	1.1	0.8	0.9	0.4	8.1
P	10	1.5	1.3	0.8	1.2	1.2	0.6	1.0	0.8	8.2
P	10	1.7	1.3	0.8	1.3	0.6	1.0	1.2	0.2	8.1
P	10	1.7	1.2	0.8	1.3	0.4	0.8	1.0	0.6	7.7
Mean		1.7	1.3	0.8	1.3	0.7	0.8	1.0	0.5	8.0
S	20	1.4	1.2	1.0	1.0	1.4	1.0	-0.2	0.9	7.8
S	20	1.6	2.1	1.0	0.2	1.2	1.2	0.9	-0.5	7.7
S	20	2.1	1.0	1.0	1.4	0.5	0.5	1.4	-0.2	7.8
Mean		1.7	1.5	1.0	0.9	1.0	0.9	0.7	0.1	7.8
P	20	2.3	1.3	1.0	1.2	0.4	0.8	1.0	0.4	8.2
P	20	3.3	1.9	-1.0	1.3	2.7	1.2	0.8	-0.2	10.0
P	20	1.0	1.2	1.2	1.5	0.8	0.8	1.7	0.0	8.1
P	20	3.6	-0.6	1.3	1.5	1.0	0.0	0.8	0.4	8.1
Mean		2.5	1.0	0.6	1.4	1.2	0.7	1.1	0.1	8.6
S	30	4.0	0.0	1.4	0.5	2.1	0.5	0.9	-0.2	9.2
S	30	0.9	1.4	0.2	1.0	3.3	-0.2	0.9	0.0	7.5
Mean		2.4	0.7	0.8	0.8	2.7	0.2	0.9	-0.1	8.4
P	30	2.5	0.4	2.1	0.2	2.5	0.4	1.2	-0.2	9.0
P	30	1.0	1.5	0.8	2.7	-0.8	1.7	0.8	0.8	8.4
Mean		1.7	1.0	1.4	1.4	0.9	1.1	1.0	0.3	8.7

† S = steel and P = plastic.

conformance between soil surfaces and thus better heat conduction. We have used package sealing tape for this. Aluminum foil, as used by Lascano and Van Bavel (1986), may be a good compromise. Whatever material is used it must also stop water movement.

Of course there are many ways to obtain bad data with MLs. Because the ML bottom is sealed, a ML - especially a short one - does not act like an infinitely long cylinder and there may be errors due to lack of drainage or, conversely, lack of water movement upward into the ML. One tactic frequently employed to reduce errors associated with the lack of water flux across the bottom is to replace the ML daily. Due to the design and operation of our experiment we do not present data for the first day nor did we use daily replacement. However, because we have shown that metal MLs conduct heat away from the surface, we have a strong suspicion that metal MLs underestimate evaporation on the first day after the soil is wetted (irrigation/precipitation). This is because soil thermal conductivity is a monotonically increasing function of water content and is highest when the soil is wettest. This means that energy gained by the surface during the day can most easily be conducted to the ML walls and then downward, away from the evaporating surface, immediately after the soil is wetted. This energy would not then be available to drive evaporation. This hypothesis deserves serious consideration and further research.

Ironically, one of the earliest reports of the use of MLs stated that the walls were made of water-proof cardboard rather than steel because the cardboard's "... heat conductivity is practically that of soil and thereby abnormal heat transfer downward is avoided" (Russell, 1939). Russell (1939) also used a spun aluminum ML bottom although he made no claim regarding heat flux across the ML bottom. Our results indicate that studies in which metal MLs or insulating caps are used may contain errors. It is recommended that the ML wall and capping material be reported along with ML dimensions.

REFERENCES

Boast, C.W. 1986. Evaporation from bare soil measured with high spatial relsolution. In A. Klute (ed.), Methods of soil analysis, Part 1. Amer. Soc. Agron., Inc, and Soil Sci. Soc. Am., Inc., Madison, WI, U.S.A.

Boast, C.W., and T.M. Robertson. 1982. A "micro-lysimeter" method for determining evaporation from a bare soil: description and laboratory evaluation. Soil Sci. Soc. Am. J. 46:689-696.

Doorenbos, J., and W.O. Pruitt. 1984. Crop water requirements, FAO irrigation and drainage paper 24. FAO, Rome.

Evett, S.R. 1989. Field investigations of evaporation from a bare soil. Ph.D. thesis, Univ. of Arizona, Tucson. University Microfilms International, 300 N. Zeeb Road, Ann Arbor, MI, 48106. Order no. 9010476.

Klocke, N.L., D.L. Martin, R.W. Todd, D.L. DeHaan, and A.D. Polymenopoulos. 1990. Evaporation measurements and predictions from soils under crop canopies. Trans. ASAE 33(5):1590-1596.

Lascano, R.J., and C.H.M. van Bavel. 1986. Simulation and measurement of evaporation from a bare soil. Soil Sci. Soc. Amer. J. 50:1127-1133.

Montgomery, D.C. 1976. Design and analysis of experiments. John Wiley and Sons, New York.

Post, D.F., D.M. Hendricks, and O.J. Pereira, 1978. Soils of the University of Arizona experiment station: Marana. College of Agriculture, Univer. of Arizona, Tucson.

Pruitt, W.O., and J. Doorenbos. 1977. Empirical calibration, a requisite for evapotranspiration formulae based on daily or longer mean climatic data? The International Round Table Conference on "Evapotranspiration", The Hungarian National Committee, International Commission on Irrigation and Drainage.

Russell, J.C. 1939. The effect of surface cover on soil moisture losses by evaporation. Soil Sci. Soc. Amer. Proc. 4:65-70.

Salehi, R. 1984. Micro-lysimeter and thermometric measurements of soil evaporation near a point source emitter. M.S. thesis, Dept. of Soils, Water and Engineering, University of Arizona, Tucson.

SAS Institute Inc. 1987. SAS technical report P-171, changes and enhancements to base SAS software for personal computers, release 6.03. Cary, NC.

Shawcroft, R.W., and H.R. Gardner. 1983. Direct evaporation from soil under a row crop canopy. Agric. Meteorol. 28:229-238.

Todd, R.W., N.L. Klocke, G.W. Hergert, and A.M. Parkhurst. 1991. Evaporation from soil influenced by crop shading, crop residue, and wetting regime. Trans. ASAE 34(2):461-466.

Touloukian, Y.S., R.W. Powell, C.Y. Ho, and P.G. Klemens. 1970. Thermophysical properties of matter. IFI/Plenum, New York. Vol. 1, p. 1113 and Vol. 2, p. 953.

Walker, G.K. 1983. Measurement of evaporation from soil beneath crop canopies. Can. J. Soil Sci. 63:137-141.